Seismic Damage-Resistant System for Multi-Storey Modular Light Steel Framed Buildings

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Abstract

Multi-storey modular construction has rapidly been gaining popularity globally over recent years, but is currently limited in high seismic regions such as NZ due to the need for a separate seismic-resisting system to prevent severe damage to the bottom level of modules. A PhD research project has been undertaken with a focus on the development of a passive energy-dissipating slider device for damage-resistant seismic protection of multi-storey modular buildings. Experimental and numerical studies have been undertaken on the system incorporating the proposed slider devices in three- and six-storey modular steel structures. It has been demonstrated through these studies that the performance of the sliding system is satisfactory.

Keywords: seismic, design, damage-resistant, modular, cold-formed, steel

1. INTRODUCTION

Modular construction has been gaining increasing popularity around the world. It involves the use of prefabricated volumetric units (known as modules) as fitted-out and serviced building blocks. Modules may be used for the rooms, corridors, stairs, lifts, and roof of a building. There are a variety of buildings that can be modular and include hotels and apartments, accommodation, educational buildings, office buildings, highly serviced units (e.g., lift shafts and industrial clean rooms), restaurants, service stations and re-locatable, temporary buildings (e.g., construction site office) and site worker accommodation (Jing and Clifton, 2016).

However, multi-storey modular buildings are currently severely limited due to seismic weaknesses in these buildings which make them vulnerable to significant damage in a moderate to severe earthquake, due to their tendency to develop concentrated inelastic demand in the lowest level of the system. This PhD research has the objective to develop a seismic damage-resistant system to allow multi-storey modular buildings to remain stable and functional during and after a major earthquake (Jing and Clifton, 2016).

2. DESIGN AND DEVELOPMENT OF PROTOTYPE DEVICE

A novel concept is proposed to create a flexible layer in the horizontal plane at each floor level of a stacked modular structure with the use of a series of sliders incorporated between modules, which are allowed to move relative to each other at different floor levels in alternate directions. The sliders have dynamic self-centring capability to ensure that all sliding modules return to their pre-earthquake positions after the severe shaking. Most of the seismic energy is dissipated through kinetic friction generated between the sliding modules to minimise the seismic damage suffered by the building (Jing and Clifton, 2016).

To achieve the novel working concept, an energy-dissipating self-centring slider device has been developed. The device consists of a bonded rubber unit (BRU), a pair of steel confining plates connected by an inner steel rod and a pair of sliding wall tracks. The BRU provides an elastic restoring force to facilitate dynamic self-centring. In a severe earthquake, the BRU moves with the module laterally at each floor level while the inner steel rod remains static. As the BRU moves, the rubber is deformed, and consequently, there is an elastic restoring force developed in the deformed rubber. The force increases with the sliding displacement and guides all modules to self-centre to the pre-earthquake positions within the typical tolerance of modular construction (Jing and Clifton, 2016).

The slider units are distributed evenly along the sides of modules in alternate sliding directions. Fig. 1 shows two horizontally adjacent slider devices incorporated in the wall tracks of four neighbouring modules at each floor level. There are four wall tracks placed in a back-to-back configuration. The ones orientated upwards are the bottom wall tracks of the two upper modules while the other two are the top wall tracks of the two lower modules (Jing and Clifton, 2016).

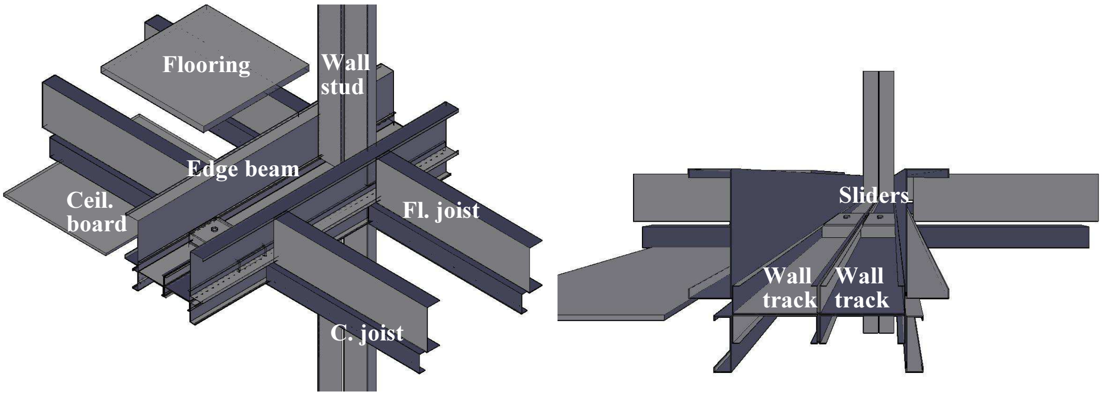


Fig. 1 Typical modular steel framing with two adjacent slider devices (Jing and Clifton, 2016)

The proposed seismic damage-resistant system will allow a multi-storey modular building to remain stable and functional during and after a major earthquake. There is a set of desired performance objectives defined as follows:

- At any level, the allowable relative displacement between modules is limited by the 2.5% drift requirement;
- All modules at all levels slide in alternate directions and subsequently return to their original positions within a tolerance of 5mm;
- At all levels, the sliding modules experience a restoring force that increases with the relative displacement;
- At all levels, the sliding modules possess a stiffness that increases with the relative displacement;
- More than 50% of the input seismic energy is dissipated through rubber hysteresis and kinetic friction generated in the damage-resistant system;
- While sliding, the structure remains stable and elastic and is not prone to any collapse, soft-storey failure at lower levels, and undesired mode of vibration (e.g., torsional mode); and
- Throughout the period of severe shaking, the structure and slider units remain fully elastic (Jing and Clifton, 2016).

3. BEHAVIOUR OF ENERGY-DISSIPATING SLIDER DEVICE

The stiffness, load-deflection hysteresis and friction characteristics of the proposed slider device have been determined through comprehensive experimental and numerical studies undertaken as part of this research. The slider device consists of two key components including a pair of BRUs and wall tracks. These components have been studied initially separately and then together as a fully assembled device (Jing and Clifton, 2016).

First, the hysteresis and nonlinear behaviour of a single BRU subjected to cyclic sawtooth-type loading with maximum displacements of 10, 15, 18, 20 and 25mm were determined through a series of 7 experimental tests (BRU-1 to BRU-7) carried out with and without the top and bottom confining plates at various static and dynamic frequencies. Fig. 2 shows the force-displacement plot from one of these tests (BRU-7) and the polynomial approximation of the test results (Jing and Clifton, 2016).

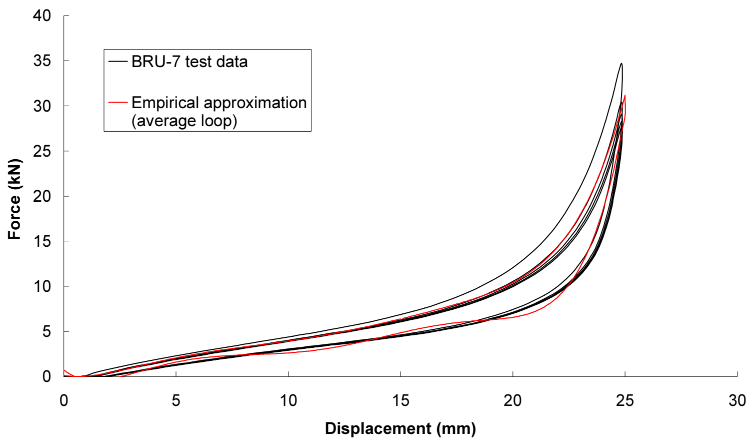


Fig. 2 Comparative plots of BRU-7 test data and empirical approximation (Jing and Clifton, 2016)

The BRU-7 test was carried out with the top and bottom confining plates at a frequency of 0.5Hz to a maximum displacement of 25mm. Five cycles of sawtooth-type loading were applied. It can be seen from Fig. 2 that at the maximum displacement of 25mm, the load-deflection curve was vertical with an infinite stiffness which indicates that the rubber was fully confined in an incompressible state, and no further displacement could be achieved. For a displacement range of 0 – 15mm, the relationship was approximately linear as shown in Fig. 2. The BRU-7 test finished with a temporary residual displacement (approximately 1.5mm), but the rubber then self-recovered completely after the test, and the inner sleeve returned to the original, unstressed position as measured before the test (Jing and Clifton, 2016).

Following the BRU tests, a further series of friction tests was completed to determine the friction characteristics of the galvanised steel wall tracks as a function of the sliding velocity, normal load and number of displacement cycles. There were 15 tests carried out on six pairs of galvanised steel wall tracks placed in a web-to-web configuration. These tests were undertaken at various frequencies (0.02, 0.2, 0.6 and 1Hz) with three different normal loads applied (1.905, 4.021 and 6.137kN) to a maximum displacement of 30mm (Jing and Clifton, 2016).

It was found that the coefficient of friction (CoF) initially remained effectively constant for the amount of sliding corresponding to several severe earthquake events. At a later point, it increased significantly due to the increase of surface roughness as the top zinc layer wore off. The average CoFs corresponding to the three different applied normal loads were close. Even though the CoFs in the test with a normal load of 1.905kN applied were slightly higher, it can be concluded that, in general, the normal load has minimal effect on the CoF prior to the first cycle of transition in which the CoF starts to increase substantially with the number of loading cycles. The variation of the CoF with the number of cycles will be negligible during a major earthquake. For the subsequent time-history analysis of multi-storey modular steel structures, a CoF of 0.144, being the average from these tests, was used to define friction links in SAP2000 to represent the sliding wall tracks (Jing and Clifton, 2016).

Finally, a study was undertaken to determine the behaviour of the fully assembled slider device incorporating a pair of confined BRUs and galvanised steel wall tracks. As part of this study, the proposed slider device was tested and modeled in SAP2000 for time-history analysis. There were 9 tests (SLIDER-1 to 9) carried out in total at dynamic frequencies (0.2, 0.6 and 1Hz) with three different normal loads (1.905, 4.021 and 6.137kN) applied, and for each test, analysis results were generated for comparison with the test data (Jing and Clifton, 2016).

Fig. 3 shows the comparative plots of the SLIDER-9 test and analysis results. SLIDER-9 was completed at 1Hz to a maximum displacement of 26mm with a normal load of 6.137kN applied. As shown in Fig. 3, the hysteresis loops consists of two components: rectangular friction loops and rubber hysteresis loops. The rectangular friction loops were generated from the sliding wall tracks only while the rubber hysteresis loops were associated with the pair of deformed BRUs. It should be noted that the gap between the inner rod and sleeve in the slider device had been removed in the final design when the analysis was competed, and therefore there were some differences between the test and analysis results (Jing and Clifton, 2016).

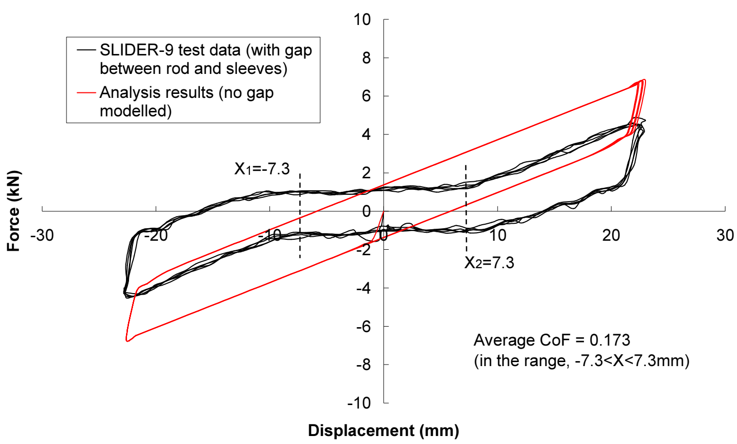


Fig. 3 Comparative plots of SLIDER-9 and analysis results (1Hz, 6.137kN) (Jing and Clifton, 2016)

4. SEISMIC PERFORMANCE OF MULTI-STOREY MODULAR STRUCTURES

In the final experimental phase of this research, a 0.25-scale three-storey stacked modular steel structure with the proposed slider devices used at each floor level was built and subjected to seismic biaxial base excitation in experimental tests, and it performed well and satisfied the desired performance characteristics as defined in Section 2 of this paper. Fig. 4 shows the test structure on a shake table (Jing and Clifton, 2016).

Fig. 4 Test structure ready to be tested on shake table (Jing and Clifton, 2016)

Two seismic tests were carried out on the test structure using the shake table to simulate 1940's El Centro ground motion. Scale factors of 1.0 and 1.8 were applied to the ground motion displacements in the first and second tests (MOD-1 and MOD-2) respectively. These scale factors were applied in addition to the scale factor of 0.25 for the test structure. The duration of the ground motion period was 34 seconds. The test structure was placed on a 45-degree angle to the direction of motion of the shake table, to generate biaxial action. Following the tests, the test structure was modeled and analysed in SAP2000, and the results were compared with the test data as shown in Fig. 5 (Jing and Clifton, 2016).

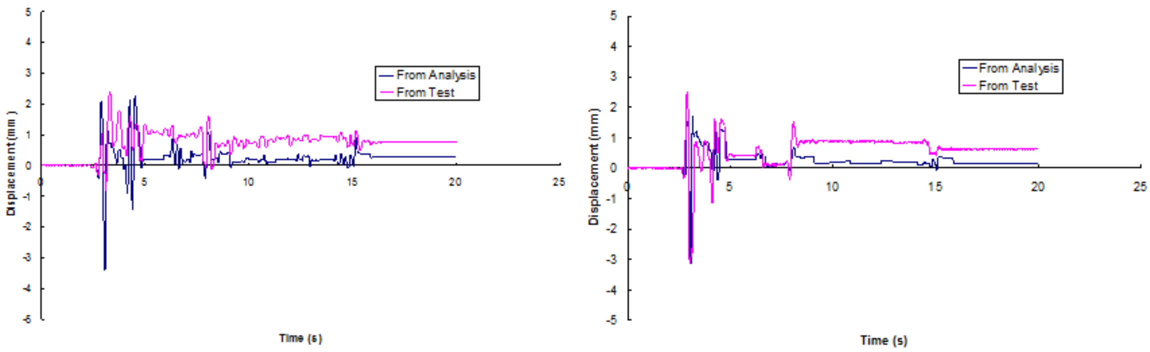
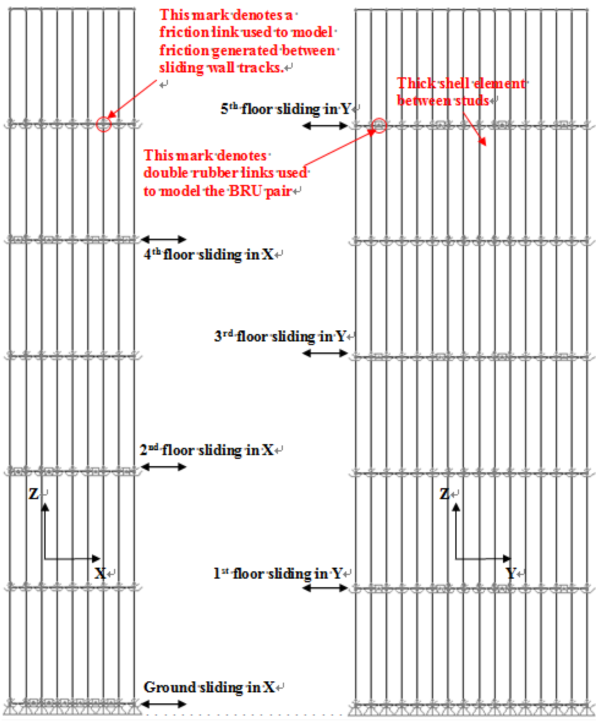


Fig. 5 Selected MOD-2 displacement plots at ground (left) and first floor (right) (Jing and Clifton, 2016)

The differences between the analysis and test results were primarily caused by the imperfections in the construction of the test structure, which were larger than what would be encountered in practice and therefore very significant on the 0.25 scale model. From the results, it can be seen that the proposed sliding friction system worked well and satisfied the desired performance objectives as defined in Section 2. Even though the maximum displacements recorded in the tests were at the 0.25 scale, they are smaller than expected.

This was in part due to the shaking table with insufficient power and capability to simulate a larger earthquake. Based on the SAP model of the test structure, a six-storey full-scale model was created (Fig. 6) and analysed using time-history analysis in SAP2000 with the use of scaled earthquake records including El Centro, Delta, Kalamata, Chihuahua, Corinthos, Westmorland and Chi-Chi (Jing and Clifton, 2016).



Notes:

1. Full-scale version of test structure but with six-storey height

2. Periods: 1.17s (X) and 1.0s (Y) calculated from modal analysis

3. Use of Delta, Kalamata, Chihuahua, Corinthos, Westmorland and Chi-Chi ground motion records

4. Accelerograms scaled to the requirements of NZS 1170.5

5. Constant modal damping of 5% applied for all modes

Fig. 6 Six-storey modular steel structure defined in SAP2000 (Jing and Clifton, 2016)

5. DISCUSSION AND CONCLUSIONS

As revealed by the analysis results, the proposed sliding system in the six-storey modular steel structure as shown in Fig. 6 is capable of achieving all the desired performance objectives as discussed in Section 2. When subjected to the scaled ground motion accelerograms applied in both the longitudinal and transverse directions, the modules slid in alternate directions at different floor levels within a maximum displacement defined by the 2.5% drift requirement and subsequently self-centred within a tolerance of 5mm at the conclusion of the severe shaking. While sliding, all modules remained stable and were not prone to any collapse and soft-storey failure at lower levels. During the severe shaking, more than 50% of the seismic input energy was dissipated through friction and rubber hysteresis in the proposed system. Also, it was found from the analysis results that there was a tendency for torsional movement to occur at the ground level. However, the torsional movements were all within the acceptable tolerance of 5mm which is the typical modular construction tolerance used in practice and therefore will not compromise post earthquake performance (Jing and Clifton, 2016).

6. REFERENCES

Jing, J. and G.C. Clifton, 2016. *Seismic Damage-Resistant System for Modular Steel Structures*. Ph.D. thesis. The University of Auckland, Auckland, New Zealand.